Bunch Frequency Multiplication in the CLIC Test Facility CTF3

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Abstract

The aim of the CLIC Test Facility CTF3 at CERN is to prove the feasibility of key issues of the two-beam based Compact Linear Collider (CLIC) study. In particular, it addresses the generation of a drive beam with the appropriate time structure to produce high power RF pulses at a frequency of 30 GHz.

The first major goal of CTF3 was to demonstrate, at low charge, the combination of successive bunch trains by RF deflectors in an isochronous ring. This bunch frequency multiplication has been successfully performed for various combination factors up to five and will be presented.

INTRODUCTION

The Compact Linear Collider (CLIC) study [1] aims at a multi-TeV (0.5 – 5 TeV centre-of-mass), high-luminosity ($8 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) electron-positron collider for particle physics. The CLIC scheme is based on the Two-Beam Acceleration concept where a low-energy, high-intensity drive beam powers the main beam of a high-frequency (30 GHz) linear accelerator with a gradient of 150 MV/m.

One main challenge of this scheme is to generate the drive beam in a low-frequency accelerator and to obtain the required high-frequency bunch structure needed for 30 GHz RF production. This bunch structure is obtained by sending the beam through an isochronous combiner ring using RF deflectors to inject and combine electron bunches, thus increasing the bunch repetition frequency.

The aim of the CLIC Test Facility 3 (CTF3) project is to demonstrate the technical feasibility of the key concepts of CLIC. In a first stage (CTF3 Preliminary Phase) [2], a low current test of the bunch train combination was performed, where the injection into the ring by RF deflectors and the multiplication of the bunch repetition frequency were demonstrated.

THE PRELIMINARY PHASE OF CTF3

The Preliminary Phase of CTF3 made maximum use of the existing hardware of the former LEP Pre-Injector (LPI) complex at CERN. Some major modifications had to be performed to adapt the installation to the new requirements of CTF3. The general layout of the facility is shown in Fig. 1 and a detailed description can be found in [3]. The machine was commissioned and operated between September 2001 and October 2002.

The CTF3 Preliminary Phase installation consists of a 3 GHz linear accelerator with a matching section, an injection line, and a combiner ring. The thermionic gun [4] of the linac produces up to seven electron pulses of 6.6 ns FWHM spaced by 420 ns, equivalent to the revolution period of the ring. The 3 GHz bunching system subdivides these pulses into trains of approximately 20 bunches each, spaced by 333 ps. The charge per bunch is about 0.1 nC, limited for the combination process by the beam-loading in the linac accelerating structures. The linac accelerates the bunches to an energy of about 350 MeV before entering a matching section to adapt the transverse Twiss parameters of the beam to the injection line optics. The following injection line is achromatic and isochronous at first order to avoid bunch lengthening.

The ring has a design circumference of 125.647 m, optimized for the combination where the condition

$$C = n\lambda_0 \pm \frac{\lambda_0}{N} \tag{1}$$

has to be met between the ring circumference C and the bunch frequency multiplication factor N. λ_0 is the RF wave length in the linac and the deflectors, and n an integer. The frequency can be slightly detuned in order to switch between different combination factors from three to five.

BUNCH TRAIN COMBINATION BY RF DEFLECTORS

The injection into the ring is done using two horizontally deflecting RF structures. They are located in the ring with a horizontal betatron phase advance of π between them to create a time-dependent local closed bump of the reference orbit. The kick strength and direction vary rapidly with

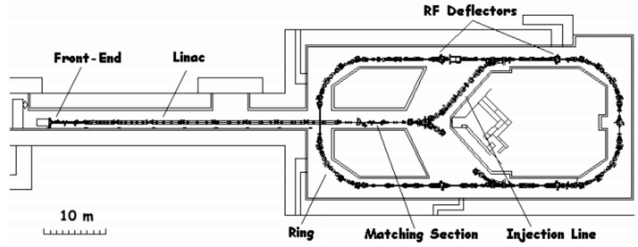

Figure 1: General layout of the CTF3 Preliminary Phase.

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time, allowing the interleaving of the bunches in the ring. Fig. 2 shows the principle of the injection with RF deflectors for a frequency multiplication factor four:

1. The bunches of the incoming train always receive the maximum kick from the RF deflector and are deviated onto the closed orbit in the ring.
2. With Eq. 1 fulfilled (for combination factor $N = 4$), the bunches arrive after one turn in the deflectors at the zero-crossing of the RF field, and stay on the equilibrium orbit. The second train is injected into the ring.
3. After a second turn, the first train bunches are deflected towards the opposite direction, the second train bunches arrive at the zero-crossing, and the third train is injected.
4. At the injection of the fourth train, the first and third train bunches arrive at the zero-crossing, and the second train bunches are kicked away from the septum. The four trains are now combined in one single train. The initial bunch spacing is reduced by a factor four and the current multiplied by the same factor.

For combination factors other than four, the phase of the deflecting field at the passage of the bunches and hence the trajectories between the two deflectors change accordingly.

The RF deflectors are short resonant, travelling-wave, iris-loaded structures with a negative group velocity. In order to obtain the nominal deflecting angle of 4.5 mrad for injection at 350 MeV, a power of about 7 MW is needed in each of the deflectors. They are powered by a common klystron with a phase shifter and variable attenuator in one

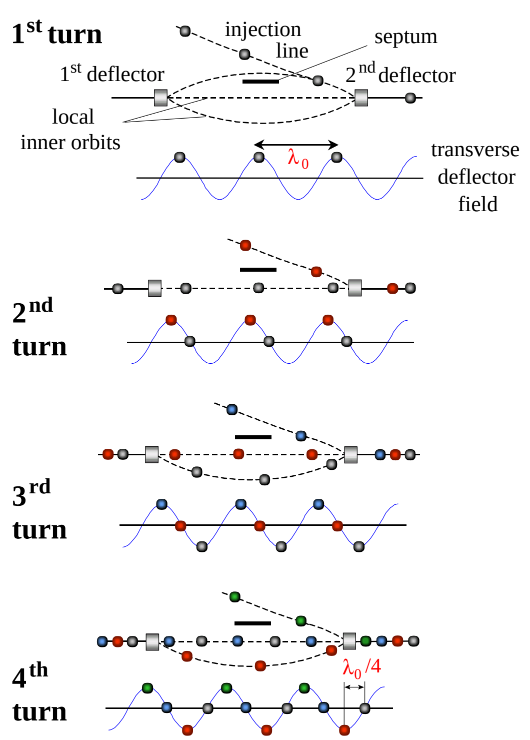

Figure 2: Bunch combination by RF deflector injection for a multiplication factor four.

of the RF network branches to allow relative phase and amplitude adjustments. Two different types of RF deflectors (built by CERN and INFN Frascati [5]) were used in two running periods of CTF3.

EXPERIMENTAL RESULTS

The linac and the combiner ring had been commissioned in 2001 [6]. The RF deflectors had been installed in the beginning of 2002. Several measurements were performed in order to prepare the bunch train combination [7]. The energy was measured after the bunching system and at the end of the linac. The beam optics was measured in the linac and found in good agreement with the design. The dispersion of the injection line was determined and one difference from the design was corrected empirically to render the line isochronous. The betatron tunes of the ring were determined for different operating conditions and were in excellent agreement with the MAD machine model. The dispersion of the ring was measured for a non-isochronous optics and showed to be very close to the model.

The bunch length is a very important issue for the combination process. The bunches must be kept short to limit the variation of the injection kick strength and the transverse extension in the injection region. Simulations have shown that about 6.5 ps rms is the maximum acceptable bunch length. The bunch length measured at the end of the linac was of the order of 3 ps rms. This imposes that both the injection line and the combiner ring have to be isochronous to avoid significant bunch lengthening. For the ring, this means that the momentum compaction factor α must smaller than 10^{-4}. A non-zero α also leads to a changing bunch distance over a number of turns in the ring due to the energy variation between the different bunches within a train created by beam loading in the linac.

The isochronicity of the ring optics was carefully tuned by changing the current in one quadrupole family while observing with a streak camera the time structure of the synchrotron light emitted in a bending magnet. Finally, the bunch distance did not change over 60 turns within the measurement error. The bunch length measured on the streak camera profiles was of the order of 4 ps rms, not changing over several turns and comparable with the one obtained at the end of the linac. Thus, within the resolution limit of the streak camera, no bunch lengthening was observed either in the injection line or the ring, proving the isochronicity as required for the combination.

The RF frequency has to be adapted for each combination factor since the path length in the isochronous ring is constant (see Eq. 1). A procedure was developed to optimize the RF frequency and both amplitudes and phases of the two RF deflectors. This procedure minimizes the injection error with respect to the closed orbit of the ring and is described in detail in [8]. A combination factor four was obtained with a frequency of $f_4 = 2.998\,585\,\mathrm{GHz}$. After the optimization, the bunch train combination showed a 100% combination efficiency. The charge multiplication could be

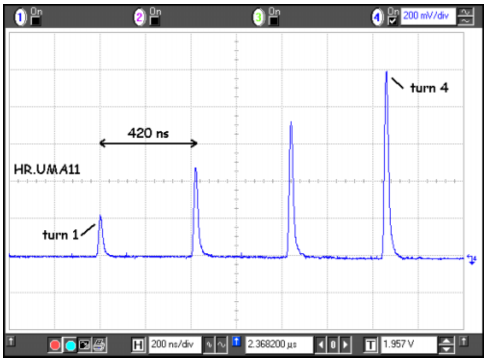

Figure 3: Intensity signal of a beam position monitor in the ring for a bunch combination by factor four.

observed on the intensity signal of beam position monitors in the ring. Fig. 3 shows that the charge increases each time a new train of bunches is combined with those circulating in the ring. The increase is not exactly linear due to pulse-to-pulse variations of the gun current.

The evolution of the time structure of the electron pulse was observed with the streak camera. Fig. 4 and 5 show typical images and corresponding intensity profiles.

For a combination factor five, the frequency was changed according to Eq. 1 and further optimized experimentally to $f_5 = 2.998\,715\,\mathrm{GHz}$. Again, a 100% combination efficiency could be obtained.

The combination performance was further studied by observing the bunch-to-bunch variations in transverse and longitudinal position [8]. Both could be minimised by the optimization procedure. Initially observed bunch spacing variations are due to the non-achromatic lattice at the observation point and could be reproduced by a linear optics model. These variations are compensated in the ejection region where the optics is achromatic.

An alternative method, based on beam frequency spectrum analysis, was also tested to monitor the frequency multiplication. A coaxial pick-up and its read-out electronics were designed and mounted in the ring to allow comparison of the amplitudes of five harmonics of the fundamental beam frequency (3 GHz) while combining the bunch trains. The commissioning of the monitor was a successful proof of principle for this new method [9].

CONCLUSIONS

The bunch frequency multiplication has been successfully demonstrated at low charge in the Preliminary Phase of CTF3. Up to five bunch trains were combined without any measurable losses.

This proof of principle is a crucial step in the CLIC study. In the next stage of CTF3 [10], the bunch train combination will have to be shown at higher bunch charge (2.3 nC) and with longer pulses (140 ns). The CTF3 Preliminary Phase has been dismantled to allow the installation of a new linac in the building for the next stage.

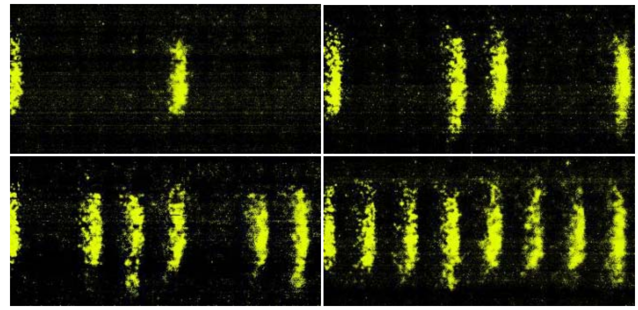

Figure 4: Bunch train combination of factor four, as observed with a streak camera. The horizontal axis represents time, the vertical corresponds to the horizontal position. The images are taken for one to four bunch trains injected.

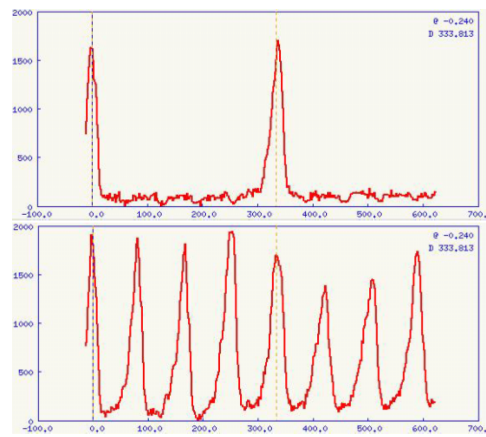

Figure 5: Longitudinal intensity profiles for a multiplication factor four. The horizontal axis is in ps. The two images correspond to injections of one and four bunch trains. Amplitude variations are again due to bunch current variations already present in the linac.

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